DESIGN OF AN ADSR ENVELOPE GENERATOR FOR A PIPE ORGAN

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Abstract

Timbre in a pipe organ is constructed by a combination of several stops, upon the basis of sound timbre reliance on spectral content, where stops would play the role of the resulting sound elemental components ("harmonics"). However this idea considers only the stationary part of spectrum, whereas it is known that its transitory part also has an influence on timbre perception. Thus, an enrichment of pipe organ's "palette of timbres" is sought, by means of giving the organist the possibility of controlling sound envelope (transient) on every stop ("stop-harmonic") individually. As a first step on the 'global project', the present work has implemented a generator electronic device giving an ADSR type envelope signal (ADSR: "Attack, Decay, Sustain & Release") to an electromagnetic actuator which controls air flow towards the pipe, with Attack, Decay & Release times and Sustain level brought about by the defined envelope signal. It is a "minimal organ" prototype (just one note, just one stop) that will allow evaluating an organ pipe response upon an air flow input modulated by an ADSR envelope, thus permitting a first empiric appraisal on the viability and 'musical sense' of the mentioned *global project* implementation in a *real organ* (for all notes, and with several stops).

INTRODUCTION: A *HARMONICS PILING PHILOSOPHY*

One of the main features in a pipe organ is the so called stops, with the function of modifying the instrument sound timbre. Concretely, the *construction* philosophy of sound in a pipe organ is based on what we define as *harmonics piling,* which consists of organizing stops as if they were the harmonics of a sound. We can see this in the diagram on figure 3, where it is showed parallelism between some of the most common stop names *("Octave", "Quint", "Terz"...)* and the harmonic they *represent* respectively, which is the one just above the stop name in the diagram. Such "harmonic *represented by a stop*" indicates in the diagram the frequencies relationship between the sound fundamental of the corresponding stop at the other side of the arrow and the sound fundamental of a "*base* stop":[1] Thus, for example, the fundamental of an " *Octave 4'* "[2] stop is at the same frequency as the "harmonic *represented* by this stop" in the figure, which is the octave harmonic *(so double frequency __2nd. harm.)* of a *base* stop.

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[1] a frequencies relation consistent with these most *common* names of stops showed in the diagram

[2] The indication *4'* in the stop name refers to the length of the longest pipe of the stop in feed ('), and corresponds to a C2 note (in musical note American notation); for ex. a *base* stop C2 pipe is 8' long. Within the *octave-type* stops, we indicate always pipe length in the name for distinguishing between the *first-octave stop (" Octave 4' ", 2nd. harmonic of a 'base' stop sound)* and the *second-octave stop (" Octave 2' ", 4th. harmonic of a 'base' stop sound).*

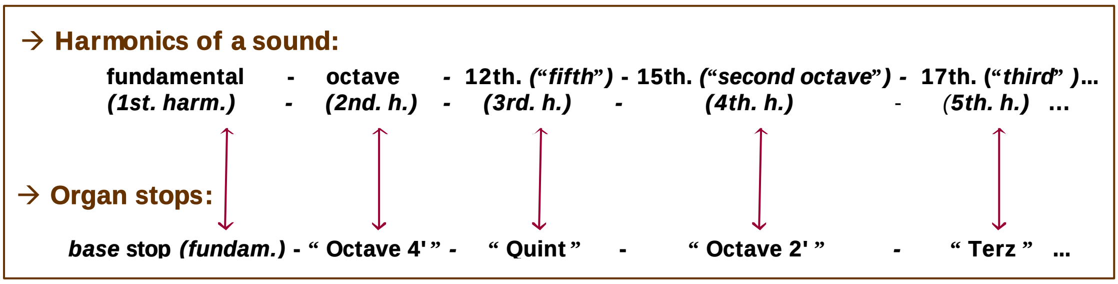
→ Harmonics of a sound:
fundamental - octave - 12th. ("fifth") - 15th. ("second octave") - 17th. ("third")...
(1st. harm.) - (2nd. h.) - (3rd. h.) - (4th. h.) - (5th. h.) ...
→ Organ stops:
base stop (fundam.) - " Octave 4' " - " Quint " - " Octave 2' " - " Terz " ...

Figure 3: Synoptic diagram showing the relation between harmonics of a sound and organ stops

According to that philosophy, pipe organ sound is *built* by means of *piling* several *"stops-harmonics"*, what has as a result a new frequency spectrum, which comes from summing the spectrum of every stop separately. We can see it illustrated in figure 4, with a *base* stop called *"Principal"* *("Principal 8' "),* and an " *Octave 4'* " stop:

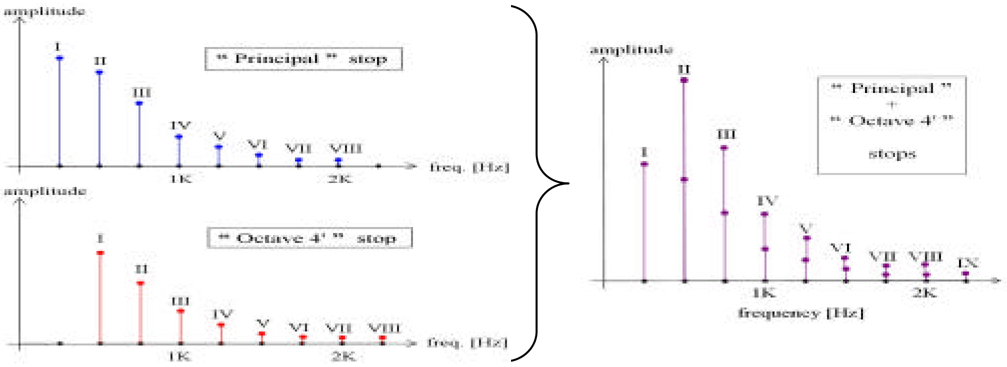

Figure 4: Schematic representation of the spectra sum produced in the combination of a base *stop called "Principal " (left, above) with an " Octave 4' " stop (left, bottom), both corresponding to a C4 note [in note American nomenclature] (~250 Hz.)*

ENVELOPE INFLUENCE ON SOUND TIMBRE

It is known that steady state harmonics distribution determine the timbre of a sound __we could somehow call this as the *"identity card of the sound"*. However, it is not less true that a sound's timbre is also affected by the transient evolution of each one of its harmonics. Indeed, such statement turns into full evidence when considering the fact that two different musical instruments (e.g. flute and clarinet) playing an identical note, on a certain tessitura, could emit a sound with equal frequency spectra, so that it is only possible to distinguish between them by observing each one's sounds initial (and final) transient [i. e. the way the note starts (and finishes) sounding, what is known too as the sound **envelope].**

It has been possible to corroborate such phenomenon, for example in an experiment carried out by Berger in 1963 [Rossing, 1982]: A group of 30 band instruments students were asked to listen to and identify samples of 10 of the same instruments they studied, where just an identical note could be listened, played individually and separately by all 10 instruments. However in all cases the initial and final 0'5 seconds of the note were cut out, so that only the stationary part could be listened to. Results reveal that the most part of instruments were erroneously identified by most of the 30 instrumentalists, what helps to make evident that often the "harmonics in steady state"-*"identity card"* is not enough for identifying an instrument (or an organ stop with respect to another one), but also transient part plays a fundamental role. Let us see in the following section how this importance of sound transients *(or envelope)* on timbrics has given us the idea of the project presented in this paper.

PIPE ORGAN TIMBRIC ENRICHMENT BY ENVELOPE CONTROL

Until now, as it has been seen above, *construction* of the diverse organ sounds is based on steady state spectrum modification, according to a *harmonics piling phylosophy*. Upon such *philosophy,* it can be established an analogy between pipe organ stops and the harmonics of a sound in general (as it is reflected in figure 3). So, according to this analogy, organ stops would be the *elementary components* of the sound resulting from their combination, in the same way as harmonics are the elementary components of a sound in general.

Then, if we can choose the *elementary components* that will constitute pipe organ sound timbre on steady state (by selecting one or another stop combination), why not to choose as well the way how each one of these *elementary components* should *appear* and *disappear* when playing a note?; thus we would increase versatility when defining the instrument's sound timbre. So our project idea is to enrich a pipe organ timbrics by influencing on spectrum's transient state, whereas on steady state we already know that spectrum can be set thanks to stop combination.

In order to achieve our objective, an envelope generator has been implemented in an electric action pipe organ, as it is showed schematically in figure 5:

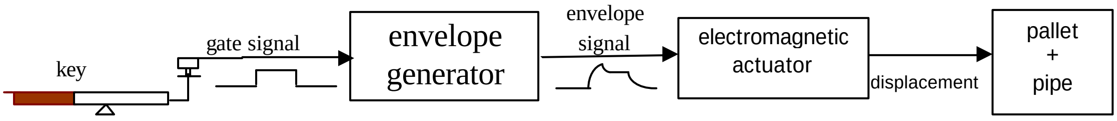

Figure 5: Block diagram of an envelope generator implemented in an electric action pipe organ

When the key is pressed, an *internal push-button (or equivalent device)* is activated and delivers a *gate signal* to the "envelope generator" block, which generates an envelope signal. Then such signal is transformed by the electromagnetic actuator into displacement of a mobile mechanical element coupled to the pallet,[3] thus opening and closing the air way in a manner following the mentioned envelope signal. So adjusting suitably the envelope generator parameters, we will control with precision note's initial and final transients, and in that sense being able to modify the timbre perception we will get from the stop in question.

Nevertheless, note that in an electric action pipe organ there are as much actuators (and a pallet coupled to each) as notes, regardless of the number of stops available in the instrument; however, if in fact our aim is to control each note envelope *(transient)* in every stop **individually,** we will need as much actuators as stops to be controlled, and of course this figure should be multiplied by the number of notes! This may reach to a significant increase in the cost of the project implementation to a *real*

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[3] In an electromagnetic actuator, the displacement of the mobile element is caused by electromagnetic force generated by one or more coils, as in the model used in the present work.

organ. For the moment, in this paper we present a prototype with only ONE key, only ONE envelope generator, applied to only ONE stop (i.e. a *minimal organ*, with only one pipe), which has been implemented as a first stage of the *global project*. This way we will be able to evaluate the response of an acoustic system such as an organ pipe __labial type in our case__, thus permitting a first empiric appraisal on the viability and *musical sense* of the *global project* implementation to a *real organ* (for all notes, and with several stops).

OVERVIEW TO THE ADSR GENERATOR MODULE

The "envelope generator" block (See fig. 5.) that has been implemented is ADSR type. ADSR signal is the most basic type of envelope signal, ever since used by electronic synthesizers to define the envelope of its sounds, and is structured in 4 phases indicated by each letter of *ADSR* acronym: (See figure 7.) It starts with the *Attack* phase in the moment in which the key is pressed (the gate signal delivered to the envelope generator is activated), growing from zero to maximum level with a rapidity brought about by the so called Attack time *(t_A)*. Just afterwards *Decay* phase is automatically initiated, where signal decreases with a *speed* brought about by a certain Decay time *(t_D)* until it reaches the *Sustain* level set for the note's steady phase *(Sustain phase);* such steady phase lasts until the key is released (Envelope generator input gate pulse is deactivated.), when *Release* phase starts, in which signal decreases from Sustain level to zero, with a rapidity determined by Release time *(t_R)*. All 4 phases are pre-adjustable *(t_A, t_D, Sustain level and t_R parameters)* by the user *(the organist in our case)*. From the instant at which the key is pressed, envelope signal generation is automatic, though we need to say that, at the moment of releasing the key, Release phase starts even if the signal hadn't reached Sustain phase. So in this last case the signal level would decrease toward zero starting from the value to which it had reached in the middle of any of the 2 previous phases' development (Decay or Attack).

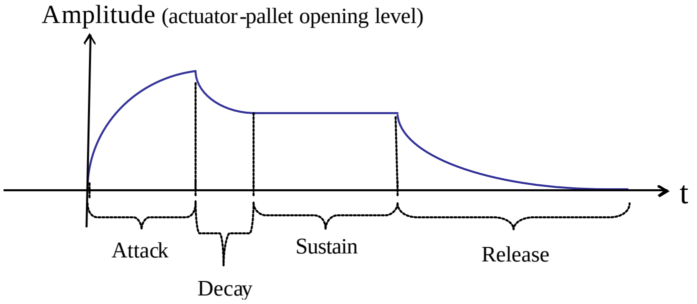

Figure 7: The four phases or stages of an ADSR envelope signal.

The curves shaping the diverse phases of an ADSR signal are of exponential kind, and are typically generated electronically by circuits based on a capacitor charging and discharging. Our generator circuit implemented in this project is founded on such circuit idea, where each t of the capacitor (charging t for t_A, discharging t for t_D and t_R, resp.) is adjustable by a potentiometer __besides, another potentiometer included in a voltage divisor for Sustain level__. The famous 555 integrated circuit *("universal oscillator")* is the circuit's *brain*, which *manages* the succession of the diverse A, D, S & R phases.

FINAL MEASUREMENTS PERFORMED ON THE COMPLETE SYSTEM

Finally let us take a look to some measurements performed yet on the complete system *(i.e. "key" + envelope generator + actuator + pallet + pipe).*[4] Two main sorts of measurements have been made on the final implementation of our "ADSR generator coupled to a pipe organ" prototype: *continuous operation* measurements and *normal operation* measurements of the system.

In the first ones, we have performed notes with minimal (virtually zero) Attack, Decay and Release times, and a Sustain level at the minimal indispensable (S˜19%) for keeping a certain pallet opening permitting a minimal air flow toward the pipe. [Below this value, the actuator was not able to compensate *external forces (pallet spring, air pressure tending to close the pallet, etc.)* and, even if the set Sustain level was not zero, the pallet ended up totally closed.] The key has been kept pressed for a long time (1, 2, 4 minutes, or more...), for checking to what extent the actuator was able to maintain unaltered the *anchor*[5] opening level in correspondence to a continuous input signal *(Sustain phase of the note)* in such critical conditions of pallet minimal opening, where system instability is higher due to the mentioned *external forces*. From the results of these measurements it emerges that, in general, in the first seconds of the note length, the actuator yields slightly to the *external forces,* tending to close a little bit the pallet, though not completely (The pipe does not stop sounding at any moment.). As time passes the opening level gets more and more stable, and even it *recovers*, in this case because of actuator warming, since it has been noticed that the actuator tends to increase *anchor* opening with a stable fix value on its input when it gets hot. This occurs when coils are obliged to do a certain continuous effort of keeping the *anchor* opened, as it is the case of these measurements.

In the other sort of measurements, the ones performed to evaluate system *normal operation,* notes with a more *reasonable* length have been played; A, D, S & R parameters have been adjusted for achieving some of the diverse envelope types which could be more useful for us __or easier to find__ in a *normal* musical performance. In these measurements we have paid special attention as well on the actuator response accuracy facing the envelope signal applied to its input. We find appropriate to comment now two aspects about such subject, exemplified respectively in the two following measurements:

* measurement 'MaximFast":[6] note with Attach, Decay and Release maximally fast, and Sustain level at maximum; this is the equivalent articulation of the one in a conventional electric action pipe organ __where there is no envelope control possibility. In figure 8 we can see some graphics corresponding to this measurement: the waveform

in time domain, and oscilloscope charts of actuator signals __input *(Ventr)*[7] and output *(Vsens).*[8] The right top picture (detail of note attack) is specially interesting to verify the **actuator real opening time:** Comparing both graphics *(Ventr and Vsens)* it will be possible to see to what extent the output signal is able to *follow* the signal *commanded* by *Ventr*, in such critical conditions of a maximally fast attack. Thus we will also evaluate in our system what is called by organbuilders the *reaction time* of the action. This is a very important parameter that designates the amount of time from the moment in which the key just starts being pressed until the moment in which the pallet just starts opening; in the case of electric action organs, as it is the case of our prototype, coils *charging* time has considerable influence on *total opening time.*[9] So we can appraise in *Vsens* signal in fig. 8 a typical inductive element charging transient (with *ringing* oscillation included). We can also observe that *reaction time* would be about 6 ms.,[10] and *total opening time* (marked with red dotted lines) would be about 20-25 ms.. (Such figure can be considered in electric action organs as *moderately acceptable*, though it has been quite shortened by some systems more recently) Likewise, in the release (right bottom picture), we can also appraise clearly the reaction delay and *ringing* oscillation of *Vsens* with respect to *Ventr*, mainly due to coils discharging transient.

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[4] As a set "pallet + pipe" it has been used a "testing organ" (a small organ with all notes but only one stop, used by organbuilders for testing pipe sets), led by Blancafort OM, an Organbuilding Company. The actuator was fixed on the frame of that "testing organ", just below the pallet (and coupled to it) chosen for testing ADSR envelope application to the air flow toward a pipe. [The "testing organ" is mechanical action; however, as for our project, within the note chosen for coupling the electromagnetic actuator to it, it behaved as an electric action pipe organ.]

[5] This is the name given to the mobile element in the actuator used. (See fig. 6.)

[6] This measurement corresponds to the one called "fNorSn1.wav" in [Guarro, 2006*b*], pp. 11-13. As it can be seen, this last name corresponds to a ".wav" file, the one where the performed note was recorded in that measurement in question. [A more detailed report of all these measurements can be found in [Guarro, 2006*b*], pp. 5-9 for the *continuous operation* ones, and pp. 10-29 for the *normal operation* ones.]

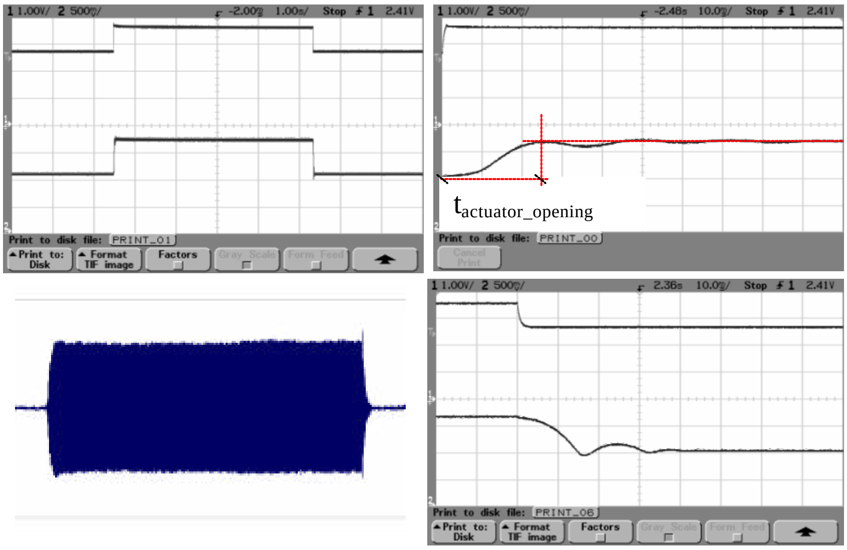

*Figure 8: **Top left,** oscilloscope chart of actuator input (channel 1, upper graphic) and output (channel 2, lower graphic) signals, corresponding to a note with an ADSR envelope with A=D=R=0, S=100% parameters ("MaximFast" measurement); **top right,** detail of note attack; **bottom right,** detail of note release; **bottom left,** waveform of the whole signal (time domain)*

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[7] The name of the actuator input signal ***Ventr*** comes from the Catalan word *"**entr**ada" (=input).*

[8] The actuator *output signal (Vsens)* is the voltage given by a Hall effect **sens**or (so this is why it is called ***Vsens***); this output voltage is proportional to the distance of the mobile element in respect of such sensor, so it reports us at all times about the opening level or shift suffered by the *anchor*.

[9] *Total opening time* will be the sum of the *reaction time* of action plus the time spent by the pallet to open completely (in this case till the *commanded* level by *Ventr* voltage).

[10] Taking into account that the pallet starts opening not before the actuator has performed a minimal shift so that all actuator-pallet mechanical coupling elements could have been tightened; such initial shift is checked to be in our system by *Vsens= 1'095 V.*

* Measurement "FirstSoundSustChange":[11] Note with maximally fast Attack, *medium values* for Decay and Release times, and Sustain level at ~30%. (See figure 9.) By this one and lower Sustain level values, it starts being noticeable a certain change in the sound of note steady phase, due to the lower air flow implied by such Sustain levels with regard to the pallet maximum opening. As for the Release phase, in this and other cases where R parameter (t_R) is set to a value higher than 0, a softer release of the note is aurally noticeable. Especially we need to remark that **the actuator tends to close the pallet faster than the way set by the input signal** (a phenomenon appraisable in the bottom image of fig. 9 __ zoom of the note release). This is due to the same *external forces* commented above (in the *continuous operation* measurements), which affected opening stability of the pallet, tending to close it.

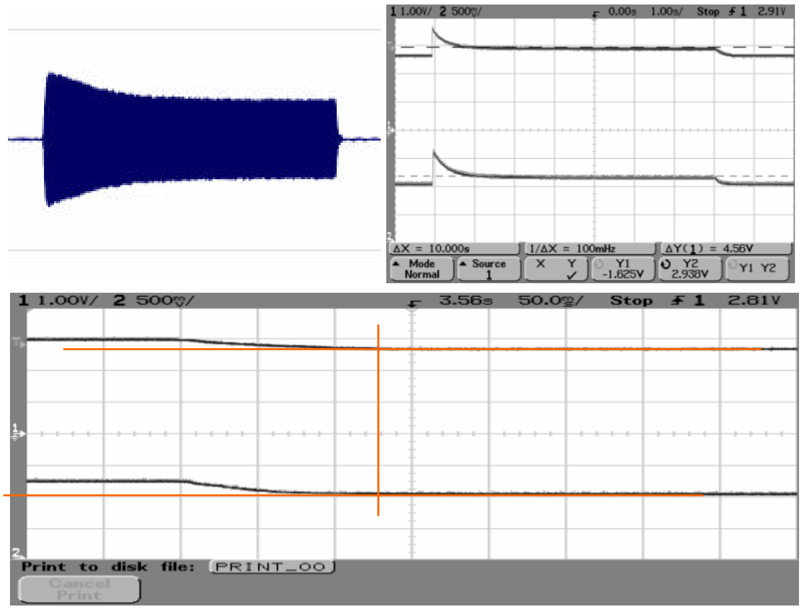

*Figure 9: **Top left,** waveform of a note with ADSR envelope with A=0, D={"medium value"}, S= 29'8 %, R={"medium value"} parameters ("FirstSoundSustChange" measurement); **top right,** oscilloscope chart of actuator input (channel 1) and output (channel 2) signals, corresponding to this note; **bottom,** detail of note release.*

SUMMARY

* The idea of this project is based on considering that timbric perception do not depends only on a note steady state harmonic distribution, but as well on initial and final evolution of each harmonic of the sound.

* Pipe Organ has always based its timbric featuring mainly on the definition of a certain spectrum in steady state by means of stops combination.

* With this project proposal __the application of an envelope for every stop individually__, harmonics distribution on a note in steady state will be kept, however there will be the possibility to modify its initial and final evolution. Thus the organ sound global timbre perception will be varied. (It will have a "different *identity card"...)*

* For it is proposed to implement an envelope generator in a pipe organ; the implementation will consist of an envelope generator module-circuit connected to the input of an electromagnetic actuator, in an electric action organ.

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[11] corresponding to the measure "fNorSn7.wav" in [Guarro, 2006*b*], p. 14

* The number of {envelope generator + actuator} blocks needed will be the number of notes multiplied by the number of stops whose envelope is wished to control individually, so the implementation economic cost in a *real organ* may reach to be high.

* Taking last point into account, it has been found convenient to implement a previous *minimal version* of the *global project,* in an organ-prototype of only one key, only one envelope generator and only one stop (just one pipe). Thus it will be possible to make a first appraisal of envelope application to an organ stop, and of the problems possibly carried by the response control of such a physical-acoustic system as an organ pipe. The implementation of this prototype is what is showed in the present paper.

* From the results and conclusions of the performed measurements *(continuous operation, normal operation...),* it emerges the need of following studying carefully the actuator response, so that it can be as much accurate as possible with regard to the *commanded* envelope signal (should the occasion arise). Such need could be made specific in the following: 1/ In fast Attack or Release transients, to achieve the {envelope generator + actuator} system (singularly the actuator) to introduce as little *reaction delay* as possible (controlling coil *ringing* too). 2/ For very low opening levels of the pallet, to achieve the actuator to compensate properly the factors interfering an appropriate sound result: one is the external forces that bring a critical instability level, in such conditions, to the *anchor* displacement; and also another one, the temperature, which, while increasing the actuator opening, could result in a variation of the pipe sound response too, specially for low opening levels, because of which small variations on air flow may imply dramatic sound changes.

ACKNOWLEDGEMENTS

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